Scripta Materialia 130 (2017) 138–142

Contents lists available at ScienceDirect

Scripta Materialia

journal homepage: www.elsevier.com/locate/scriptamat

Regular article

Dislocation characteristics of shear bands in metallic glasses

Alexei Vinogradov [a,*], Mikhail Seleznev [b], Igor S. Yasnikov [b]

[a] Norwegian University of Science and Technology, Trondheim 7491, Norway
[b] Togliatti State University, Togliatti 445667, Russia

ARTICLE INFO

Article history:
Received 23 October 2016
Received in revised form 15 November 2016
Accepted 16 November 2016
Available online xxxx

Keywords:
Metallic glasses
Shear bands
Digital image correlation
Dislocations

ABSTRACT

Using a digital image correlation technique, we measured the spatial displacement distribution around the shear band tip terminated in a deformed bulk metallic glass. The excellent agreement is found between the experimentally observed and theoretically predicted displacement fields for dislocations, which provides a direct evidence for the dislocation-like behaviour of the shear bands in metallic glasses.

Although crystal lattice dislocations obviously cannot exist in amorphous solids, the inhomogeneous deformation of metallic glasses (MG), which occurs via narrow shear bands at low homologous temperatures [1,2], bears a striking similarity with the dislocation-like flow in crystals [3]. The apparent similarity of the geometry of the shear bands in metallic glasses and dislocations in crystals has inspired J.J. Gilman [4,5] to formulate one of the historically first models of the inhomogeneous plastic flow in metallic glasses based on the dislocation concepts. The dislocation idea has not become well received in the scientific community because of difficulties of direct observations of dislocations in amorphous solids. However, quite generally, direct evidence for the actual mechanism of plastic flow in MGs is still limited and numerous microscopic observations have not yet provided incontestable evidence for any concept of the deformation mechanism [6,7]. Although the shear bands tend to propagate across the whole sample, some of them terminate inside the body under load, Fig. 1, which is largely controlled by the gradients in the stress fields within the loaded specimen. Two geometries of the shear bands resembling morphologically the edge and screw dislocations in crystalline solids are common in numerous observations reported in the literature as illustrated in Fig. 1, showing the slip offset that initiates at the surface and terminates inside the bulk MG. Usually dislocations in media have a mixed character and edge and screw dislocations are the ideal extremes, which can be distinguished on the basis of their morphology on different sides of a rectangular prism specimen deformed in compression. The line that separates the slipped from the unslipped area is by definition a dislocation in a continuum media. Such a dislocation is obviously not a dislocation having a well-defined Burgers vector in the crystallographic sense. Rather, it is a generalized dislocation of the Somigliana type having no constant Burgers vector [8]. The dislocations as linear defects in solids have been proven to exist in non-crystalline media such as the Earth crust [9], granular solids [10], quasi-crystals [11] and graphene [12]. Despite the apparently different microscopic nature of all these defects in the absence of a crystalline lattice, they have a most prominent feature, an 'identity card', uniting all dislocations and defining them as structural defects of common genesis - the characteristic elastic displacement (or strain) and stress field around the dislocation line. Volterra [13] was the first to introduce dislocations in a rigorous mathematical sense using pure linear continuum mechanics formulations which do not require a crystal structure for a dislocation to exist. Chaudhari and co-workers [14] introduced the screw and the edge Volterra dislocations into an amorphous Lenard-Jones solid and showed that elastic stress fields associated with these defects are similar to those in crystalline solid models. They demonstrated that simulated dislocations are both stable and mobile in amorphous solids [15]. If therefore a shear band in a MG can be regarded as a linear dislocation-like defect, it should create an elastic displacement field around its tip, which should be similar to that of classical Volterra dislocations.

An accurate measurement of strain distribution around the shear band in a MG would therefore serve as a touchstone, allowing identification of the nature of inhomogeneous plastic flow. Using the modern digital image correlation (DIC) technique, we endeavour to demonstrate that the shear bands forming during inhomogeneous plastic deformation in MGs can be regarded as dislocation-like defects having long-range stress fields and characterized by a displacement field similar to that of a macro-dislocation, i.e. a dislocation whose Burgers vector is not necessarily commensurate with the inter-atomic distance and can take much larger values. Mapping displacement fields using DIC

* Corresponding author.
E-mail address: alexei.vinogradov@ntnu.no (A. Vinogradov).

http://dx.doi.org/10.1016/j.scriptamat.2016.11.017

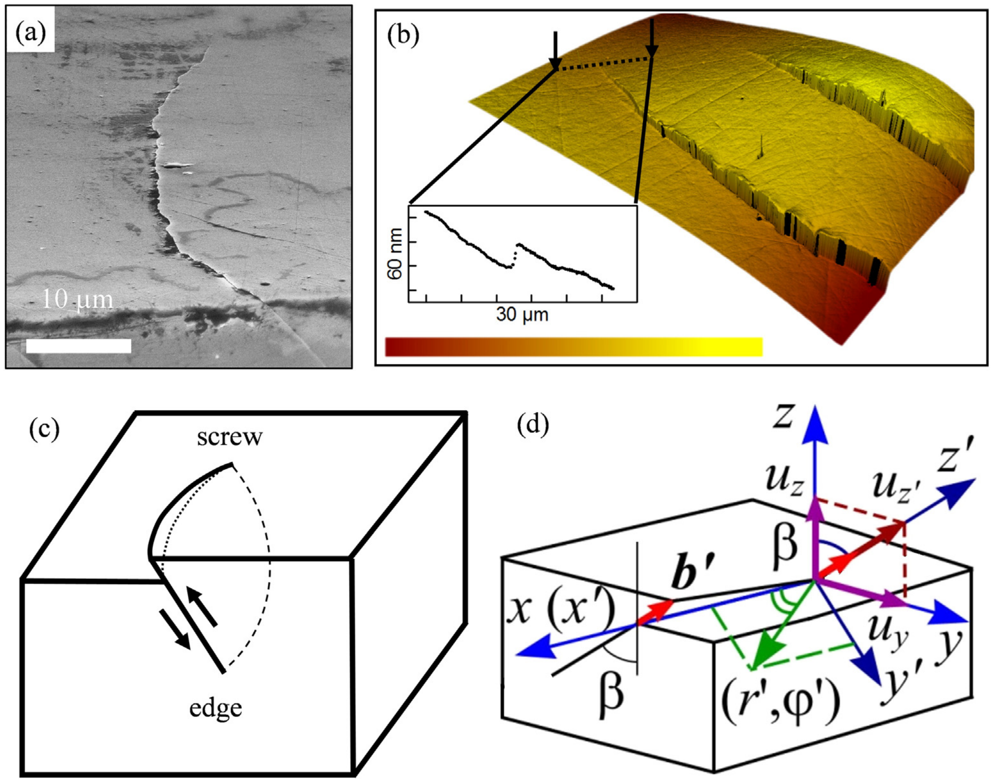

Fig. 1. An example of the investigated SBs: SEM image (a); WLSI 3D surface map with the colour range - 0.6 to 0.5 μm (b); a line profile marked by arrows on (b) is shown on the inset; schematic drawing of the SB containing both screw and edge components (c); the geometry of the observed "screw" type shear and the associated coordinate systems (d).

microscopy, which measures displacement fields by tracking features on the specimen surface with a random speckle pattern, has been proven very useful in characterizing strain heterogeneities [16].

The $3 \times 3 \times 6$ mm^3 specimens of the as-cast $Pd_{40}Cu_{30}Ni_{10}P_{20}$ glassy alloy were notched by spark erosion to limit the field of optical microscopic observations and to provoke shear band nucleation and propagation within the field of view. They were compressed using a rigid testing system [17] synchronized with the in-situ microscopic optical image recorder PIKE F-100 having the 1000×1000 pixel CCD sensor and operating at 60 frames per second. The maximum optical resolution was of 1.290 μm/pixel. Selected-field displacement/strain measurement was performed using the 2-dimensional DIC VEDDAC™ 6.0 software package. When the shear band initiated, the test was interrupted automatically using the feedback acoustic emission signal generated by the shear band and recorded during the test as described in detail in [17,18]. The successive frames were processed for displacement calculation that allows resolving displacement beyond the image resolution using a subpixel algorithm with enhanced lateral resolution to approximately 0.01 pixel.

The terminated bands representing both types of morphologies shown in Fig. 1 on different sides of the specimen were systematically observed under compression in-situ and then analysed by DIC. The shear bands with different offsets were observed. Typical results of measurements of displacement components around the terminated shear bands are shown in Figs. 2a and 3a for the "screw" and the "edge" type shear bands, respectively.

To compare the observed results with those predicted for the macro-dislocation, the actual shear geometry has to be taken into account. As is commonly observed by scanning electron microscopy (SEM), the shear offset at the surface is inclined to the surface. Consider the displacement field of a screw dislocation, Fig. 1a, with a Burgers vector perpendicular to the plane of observation [19]:

$$u_x = u_y = 0; \quad u_z = \frac{b}{2\pi} \arctan\left(\frac{y}{x}\right) = \frac{b}{2\pi}\varphi \tag{1}$$

where u_x, u_y, u_z are displacement components in the Cartesian coordinate system (CCS), φ is the polar angle in the $x-y$ plane, Fig.1d and b is the magnitude of the Burgers vector oriented along the z axis, which is associated simply with the measure of the shear offset at the free surface in amorphous solids. If the dislocation is tilted at an angle β in $y-z$ plane, the Burgers vector b' is associated with the local CCS $x'y'z'$ where the displacement field will be expressed similarly to Eq. (1) with corresponding replacement of all variables: $u_{x'} = u_{y'} = 0$ and $u_{z'} = b'\varphi'/2\pi$. As a result of this rotation, the non-zero displacement components arise on the xy plane, Fig. 1d, i.e. $u_x = u_{x'} = 0$; $u_y = u_{z'}\sin\beta$; $u_z = u_{z'}\cos\beta$. Considering the function $\Phi(x,y)$, which transforms the Cartesian coordinates x and y into a polar angle φ in the first quadrant, $\Phi(x,y) = \arctan(y/x)$ the y component u_y^s of the displacement field created by a tilted screw dislocation can be expressed as:

$$u_y^s = \frac{b'\sin\beta}{2\pi}\Phi(x\cos\beta, y) \tag{2}$$

where $b'\sin\beta$ is obtained directly from the experimental displacement measurements at the edge of the specimen: $b'\sin\beta = |u_{y\max}| - |u_{y\min}|$, Fig. 1.

The shear band initiates at a surface inhomogeneity and propagates into the bulk. Overall, the size of the macroscopic shear band terminated in the deforming volume of the typical MG is comparable to the size of the specimen. Under given circumstances, the effect of the image forces associated with the surface, represented by an 'image dislocation' [20] on the resultant stress and displacement field is significant. Taking into account the corresponding displacement component due to the image screw dislocation, the resultant displacement field for the screw dislocation inclined at the angle β to the surface reads as:

$$u_y^{res\ s} = u_y^s + u_y^{im\ s} = \frac{b'\sin\beta}{2\pi}\left(\Phi(x\cos\beta, y) + \Phi(-(x+2d)\cos\beta, \ -y)\right) \tag{3}$$

where d is the distance from the dislocation core to the free surface.